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Absorption and Scattering of Mercury
Vapor for the Line 2536

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ABSORPTION AND SCATTERING OF MERCURY VAPOR
FOR THE LINE 2536

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ABSTRACT

A beam from a mercury arc is passed through a vessel filled with mercury vapor of 16.2°C, and excites in it resonance radiation of wave-length 2536. The absorption coefficient and the scattering coefficient of this radiation have been measured. It was found: (a) the absorption coefficient is 1 cm^{-1} and is not changed measureably by the admission of air up to 4 mm pressure, although the resonance radiation is strongly quenched by the air; (b) in vacuum the scattering coefficient is equal to the absorption coefficient within the limits of the experimental error. This proves the assumption first made by Wood that in vacuum there is no true absorption, but that the whole loss of energy is due to scattering. For higher pressures, the scattering coefficient diminishes. The data found are in good agreement with previous direct measurements of Wood and Stuart.

IF THE light of the mercury emission line 2536 passes through mercury vapor, it is absorbed. The absorbed energy can either be transformed into heat (true absorption) or it can be re-emitted as resonance radiation, as was found by Wood.¹ The presence of other gases diminishes the amount of resonance radiation, as found by Wood,² Stuart³ and others.

According to the classical theory, the total absorption of mercury vapor for the line 2536 should be the same in the case of mercury vapor alone as for mercury vapor in the presence of another gas. From measurements of Fuchtbauer, Joos and Dinkelacker⁴ and Trumphy⁵ it follows that the total absorption is changed by other gases of many atm. pressure. Their method of measuring the total absorption was based upon the fact that the line 2536, in the presence of a gas at high pressure, appeared so wide that several photometric determinations could be made across the line. The increase in the width of the absorption line by the admission of air to the exhausted tube containing the vapor was observed by R. W. Wood.⁶

In the present investigation, a method was employed which enabled measurements to be made of the total absorption in both cases, and, at the same time, of the true absorption, as distinguished from scattering (resonance radiation).

GENERAL DESCRIPTION OF THE METHOD

If a nearly parallel beam from a mercury arc passes through an evacuated quartz vessel filled with mercury vapor it excites resonance radiation which

¹ R. W. Wood, *Phil. Mag.* (6) **23**, 689 (1912); *Phys. Zeits.* **13**, 353 (1912).

² R. W. Wood and M. Kimura, *Phil. Mag.* (6) **32**, 329 (1916).

³ H. A. Stuart, *Zeits. f. Physik* **32**, 262 (1925).

⁴ C. Fuchtbauer, G. Joos and O. Dinkelacker, *Ann. d. Physik* **71**, 204 (1923).

⁵ B. Trumphy, *Zeits. f. Physik* **40**, 594 (1926).

⁶ R. W. Wood, *Physical Optics*, p. 488.

can be photographed. The decrease of this resonance radiation along the primary beam which is proportional to the decrease of the intensity of the radiation (capable of exciting resonance) in the primary beam itself, enables us to measure the total loss of energy (true absorption and scattering) along the primary beam in the mercury vapor. This method has been applied first by Wood,² then by Goos and Meyer⁷ for the same purpose, but they did not make detailed measurements with different pressures of added gas. Hughes and Taylor have published new measurements on the subject by a different method in a paper which appeared after the completion of this investigation.⁸

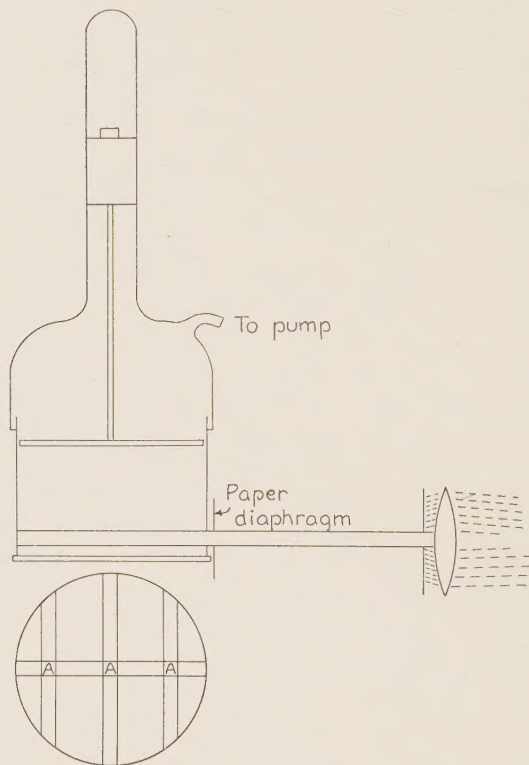


Fig. 1.

The resonance radiation from the primary beam in its outward passage excites the atoms in parts not illuminated directly by the primary beam, giving rise to secondary radiation, and by comparing the intensity of this with that of the resonance radiation from the primary beam we can calculate the absolute amount of scattering. To test this value the depth of the vessel in the direction perpendicular to the primary beam was varied by means of a movable disk covered with smoke to avoid reflection.

⁷ F. Goos and H. Meyer, *Zeits. f. Physik* **35**, 803 (1926).

⁸ A. L. Hughes and A. R. Thomas, *Phys. Rev.* **30**, 466 (1927).

APPARATUS

The mercury resonance lamp was constructed from an open cylinder of fused quartz, to one end of which was sealed a glass tube. Within the vessel was a metallic disk attached at right angles to a glass rod which was connected to an iron cylinder, sliding in the glass tube. This could be moved to and fro by means of an electromagnet. The metallic disk was uniformly covered with turpentine smoke. On the outside of the plate which closed the vessel were fixed three narrow strips of a cellophane film, which were used as intensity marks. The transmission of the film strips for the line 2536 was tested by Professor Pfund and found to be 43 percent. The mercury resonance lamp was set up in a box which contained a thermo-regulator, the sensitivity of which was 0.2°C . The temperature inside the box was kept constant by means of a red incandescent lamp which was turned on or off by a telegraphic relay connected with the thermo-regulator. A camera, furnished with a quartz lens faced the resonance lamp, in a direction perpendicular to the exciting beam. The mercury arc, which excited the resonance lamp, was cooled with running water and air, and pressed against the front of the lamp by a magnetic field to avoid reversal. The light was focussed by a system of quartz lenses on the mercury resonance lamp, the lens nearest the resonance lamp having a diaphragm to make the beam nearly parallel. The illuminated side of the resonance lamp was covered with black paper perforated by a small rectangular opening, giving the primary beam a height of 4 mm and a depth of 2 mm. The resonance lamp was exhausted by a mercury vapor pump, and the pressure read by gauges, one reading between 10^{-2} and 10^{-4} mm, the other from 0.1 to 10 mm. Air was admitted to the system through a set of drying towers.

METHOD OF OPERATING

After obtaining a vacuum of at least 10^{-2} mm and a constant temperature of 16.2°C , the arc was lighted, the beam made parallel to the front plate of the resonance lamp, and the diaphragm in front of the arc focussed by means of a barium platino-cyanide screen on the opening of the black paper covering the resonance lamp. The center of the opening was 6 mm behind the front plate. In spite of the fact that neither visible nor ultra-violet light hit the front plate, one could see with a rested eye a faint bluish light in the whole mercury resonance lamp which was more intense where the beam passed through. This light was probably scattered from the walls of the cylinder, but it was found to have no measurable effect on the photographic plate.

Next, four different series of exposures were taken. In the first, the mercury vapor alone was present. Next, three series were taken for different pressures of air in the resonance lamp, namely 0.4, 1.5, and 4 mm. For each pressure the disk inside the resonance lamp was placed in three different positions. In the first it was very near the primary beam but did not touch it, in the second and third it was pushed back. The position of the disk was known by reading the shadow of the iron cylinder upon a fixed scale. A fourth

exposure was taken with an absorption vessel before the arc. It consisted of a highly exhausted quartz bulb containing mercury vapor. The purpose of this was the following:

As the emission line from the mercury arc is much broader than the absorption line from the resonance lamp, the absorption coefficient would not be the same for the different parts of the emission line so that in the beam the center of the line would gradually be abstracted on its way through the vessel, and therefore the average absorption coefficient would be diminished. Besides, the outer parts of the line will excite less resonance radiation, so that for these outer parts the ratio between the secondary and the primary radiation would be smaller. If we now introduce the absorption vessel the center of the 2536 line in the exciting light is cut out, and the intensity observed is then due entirely to the outer parts of the line. If we subtract this intensity from the intensity observed without the absorption vessel, we get the effects due to the center of the exciting line alone.

The plates were developed in Eastman-Kodak developer at constant temperature, and with equal times of development.

EVALUATION OF THE PLATES

The photographic plates were measured on the recording densitometer at Princeton University.* On every curve was marked the zero for the densitometer and the fogging of the plate. To get the relation between densitometer readings and the corresponding intensities of the light, one should print intensity marks on each plate. Instead, the following simpler method was used. On all plates the photometer readings inside a cellophane absorption-strip were taken. For the same place the photometer reading was found which would be there without the absorption strip by extrapolating from both sides. Each plate should give nine sets of this kind (three strips each measured in the primary beam, and 4 and 8 mm above), but not always could all nine measurements be made. We then plot (Fig. 2) the photometer readings inside of an absorption strip against the corresponding extrapolated readings. It appears that the points from all plates fall very closely on the same curve which was drawn so as to best fit them. From this the relation between photometer readings and intensity was obtained in the following way:

We call arbitrarily the intensity belonging to the reading 4.5 of the densitometer 1000. The corresponding reading inside the strip would be 9 according to the curve. As the strip has a transmission of 43 percent, the corresponding intensity will be 430. We must now determine which photometric reading we would get inside the strip at a point where the extrapolated intensity would be 430 and, therefore, the extrapolated reading 9. We find on the curve the value 18.5, the corresponding intensity of which is $0.43 \times 430 = 184.9$. We proceed in the same manner and find that the photometric

* We wish to express our thanks to Professor K. T. Compton for his permission to use this instrument.

reading inside of a strip would be 33.5 if the extrapolated reading is 18.5. Therefore, the intensity corresponding to the photometric reading 33.5 is 0.43×184.9 . In this way a curve giving the intensities for every photometric reading was found.

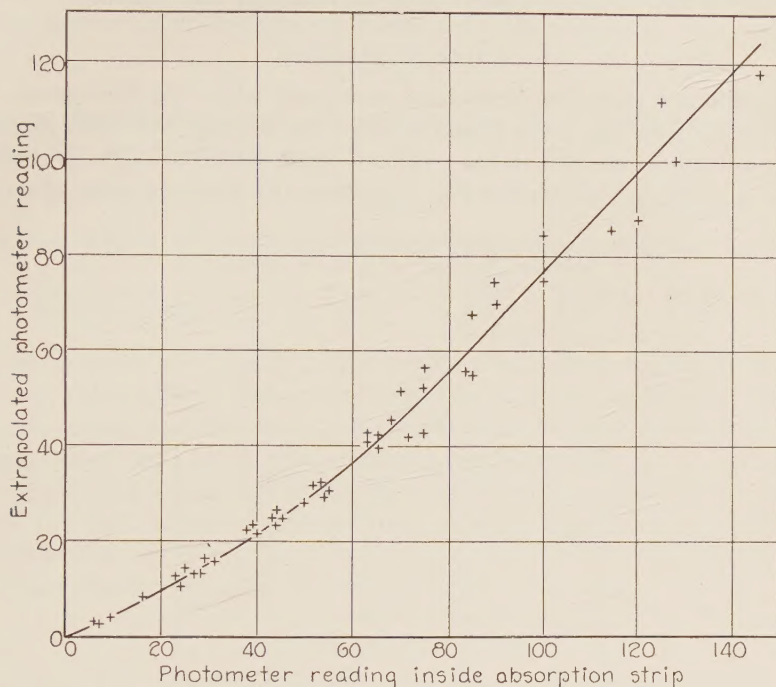


Fig. 2.

In the evaluation of the plates the photometric readings for a number of successive places were taken from the records of the densitometer. The curve gives corresponding intensities. The intensities corresponding to the fogging of the plates were subtracted from these values. The position of

TABLE I

Intensities of resonance radiation in primary beam and at various distances from it.
Mercury vapor at 16.2°C , no foreign gas.

Primary beam		Secondary radiation 4 mm height		Secondary radiation 8 mm height		Primary Beam after passing through absorption vessel	
<i>D</i>	<i>I</i>	<i>D</i>	<i>I</i>	<i>D</i>	<i>I</i>	<i>D</i>	<i>I</i>
8.75	1020	8.75	245	6.75	100		
12.75	425	15.75	85	8.75	91	3.75	101
19.75	177	19.75	55	14.75	48	8.75	83
28.75	72	28.75	22	19.75	29	15.75	71
32.75	54			28.75	9.5	21.75	46
				32.75	6.5	25.75	35

each spot was fixed by measuring the horizontal distance from the first absorption strip, the vertical distance from the middle of the primary beam.

Table I gives an example for vacuum with the disk close to the primary beam. D is the horizontal distance (in mm) from the place where the beam enters the vessel; I , the intensity after subtracting the fogging.

TOTAL ABSORPTION

We subtract now the intensities measured with the absorption vessel before the arc from the main values as described on page 562. The logarithms of the resulting intensities in the primary beam which are due to the center of the line alone, are plotted in Fig. 3 against the distance (disk close to the

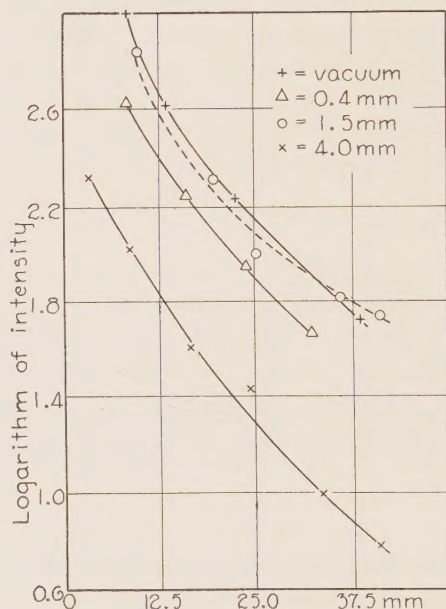


Fig. 3.

beam). The slope of these curves gives the absorption coefficient. As the figure shows the curves are parallel for all pressures in spite of the fact that the resonance radiation at 4 mm pressure of air is less than one-half of the radiation in vacuum. (Wood, Stuart.) The intensity of the primary beam for 1.5 mm pressure is in our experiment about the same as for vacuum (the curves coincide practically), while it should be about 60 percent. On the other hand, the radiation for 4 mm is ten times smaller than in vacuum while it should be only four times as small. This must be explained by changes in the mercury arc from one measurement to the other. These changes will not affect our results because we have to compare only intensities on the same plate to evaluate absorption and scattering.

The fact that the curves are parallel means that the absorption coefficients are not changed by 4 mm of air in agreement with the classical theory. It

should be mentioned that the pressure of 4 mm is far too small to alter the width of the line.

If the absorption were constant along the beam the curves would be straight lines. This is not true, but the deviation is not large, less than it would have been if the effects of the outer part of the line had not been subtracted.

If we define the absorption coefficient α by the equation

$$I = I_0 e^{-\alpha z}$$

where z is the distance along the beam we get the following average value over the distance from 0 to 18.5 mm:

TABLE II

Absorption coefficient of mercury vapor (pressure that of the saturated vapor at 16.2°C) in the presence of air at various pressures.

Air pressure:	0 mm	0.4 mm	1.5 mm	4 mm
Absorption coefficient:	1.09	0.95	1.09	0.90

giving as average $\alpha = 1 \text{ cm}^{-1}$. This means a reduction of the intensity to half of its value over a distance of 7 mm in excellent agreement with the results of Wood and of Goos and Meyer who worked in vacuum (pure mercury vapor) and at slightly different temperatures.

If we plot the intensities of the primary beam after preliminary passage through the bulb of mercury vapor (the primary resonance now being due to the outer part of the exciting line 2536) we get for α 0.3 to 0.5. As expected, the value is smaller than the one for the center of the line.

SCATTERING COEFFICIENT

If a beam of light of intensity I passes through a volume element $dx dy dz$ the amount of light scattered will be proportional to I , to the size of the element and to a coefficient β , the scattering coefficient, the scattered light being $\beta I dx dy dz$.

The calculation of the absolute value of β from our measurements would demand an exact formula for the distribution of scattered light through the whole vessel for all values of β . Unfortunately the mathematical difficulties are too great, and therefore, an approximate calculation had to be made.

Assume that we have a parallel primary beam of light. We measure x upward, y in the direction away from the observer and z along the beam. The intensity would be

$$I = I_0 e^{-\alpha z}$$

We will assume that the resonance radiation is unpolarized (rather high pressure and stray magnetic fields). Then a volume element in the primary beam will emit an amount of scattered light equal to $\beta I dx dy dz$. If we photograph a volume element emitting an amount of light $I' dx dy dz$ with a camera, the axis of which is parallel to the y axis, the intensity on the photographic plate will be proportional to the amount of light emitted divided by $dx dz$, the cross section of the source normal to the line of vision,

and multiplied by a constant B which depends on the aperture of the camera. The intensity will therefore be $e^{-\alpha y} B I' dy$, dy being the depth of the source in the line of vision. In our case this will be $B \beta I dy e^{-\alpha y}$, y being the distance from the source to the window.

Now the light emitted from this volume element will produce in another volume element $dX dY dZ$ a secondary radiation of the amount $\beta dX dY dZ (1/4\pi r^2) e^{-\alpha r} \beta I dx dy dz$. The intensity of this radiation on the photographic plate will be

$$B e^{-\alpha Y} \beta dY (1/4\pi r^2) e^{-\alpha r} \beta I dx dy dz$$

because now the cross section is $dX dZ$, the radiation has to penetrate the further distance Y through the mercury vapor while the geometric condition which determines B is the same as in the primary beam. We get, therefore, for the ratio between the intensity at the place X above the primary beam compared with the intensity in the primary beam

$$(\beta \times 0.4 / 4\pi) \int dY \cdot \int dz e^{-\alpha(Y-y_0)} e^{-\alpha(z-z_0)} e^{-\alpha r} / r^2$$

Here we have assumed that the primary beam has so little depth and height that the integration over x, y can be replaced by a multiplication with its cross section 0.2×0.4 cm square. We measure x and y from the middle of the primary beam and make our calculation at a place $z_0 = 0.875$ cm (meaning the horizontal distance from the place where the beam enters the vessel). The calculation was made for the height $X = 0.4$ and 0.8 cms for which the intensities were determined photometrically. We call the intensity of the primary beam I_1 , the intensity for 0.4 cm I_2 , for 0.8 I_3 . The integration was performed graphically for different values of Y , and the result integrated graphically over Y . We find as contributions of the directly excited fluorescence radiation

Disk at front		Disk at back	
$X = 0.8$	$0.0328 \beta I_1$	$X = 0.8$	$0.0445 \beta I_1$
$X = 0.4$		$X = 0.4$	$0.15 \beta I_1$

We next take into account the exciting effect of secondary radiation from other places. For this purpose we proceed in the following way: The layer in the height 0.8 is acted upon by the secondary radiation coming from the layer between the primary beam and the considered layer. This exciting layer has the same height of 0.4 cm as the primary beam, an average distance 0.4 cm from the considered layer 0.8 , and a measured intensity of emitted light, namely, I_2 . Closer consideration shows that it does not matter much that in this case the source of radiation is spread out into a layer instead of being a narrow beam. Therefore, the layer 2 acts on the layer 3 in the same way in which the primary beam acts on the layer 2. Finally, the layer three will excite the layer 2 in the same way in which the layer 2 excites the layer 3.

As last correction we take into account the excitation by the secondary radiation from the considered layer itself. For this purpose we divide the layer into a number of parallel beams, among which the intensity distribution has been calculated previously. Adding these the influence of the layer on itself turns out to be $0.4 I$. We therefore get the following formula:

$$I_2(\text{calc.}) = \beta(0.15I_1 + 0.4I_2 + 0.15I_3)$$

for the layer at $X = 0.4$ independent of the position of the disk.

$$I_3(\text{calc.}) = \beta(0.0445I_1 + 0.15I_2 + 0.4I_3)$$

for the layer at $X = 0.8$ with the disk back or in the middle,

$$I_3(\text{calc.}) = \beta(0.0328I_1 + 0.15I_2 + 0.4I_3)$$

with the disk in front.

The results are shown in Table III.

TABLE III

Scattering coefficient for mercury vapor (pressure of saturated vapor at 16.2°C) for various pressures of air added.

Air pressure in mm.	Pos. of Disc.	$X = 0.4$		$X = 0.8$	
		β	β (ave.)	β	β (ave.)
0	Front	0.92	1.06	0.86	0.90
	Middle	0.95		1.03	
	Back	1.30		0.82	
0.4	Front	0.86	0.85	0.81	0.76
	Middle	0.99		0.83	
	Back	0.71		0.65	
1.5	Front	0.55	0.69	0.42	0.47
	Middle	0.85		0.44	
	Back	0.67		0.62	
4	Front	0.54	0.65		
	Middle	0.77			

If we compare the values of β average in the table with the data of Wood² and Stuart³ for the quenching of the resonance radiation we find:

TABLE IV

Comparison of relative scattering coefficient with results of Wood and of Stuart.

Pressure	Layer 0.8 cm	Layer 0.4 cm	Wood	Stuart
0	1	1	1	1
0.4 mm	0.84	0.80	0.80	0.78
1.5 mm	0.52	0.65	0.60	0.43
4 mm		0.61	0.40	0.25

Except for the highest pressure the agreement is as good as can be expected. The absolute value of β in vacuum, 0.98 as average between the two layers is identical in the limits of the errors of observation with the absorption

coefficient α , confirming an opinion expressed by Wood as early as 1912 and since this time often repeated that in vacuum there exists no true absorption but that the whole loss of energy in the primary beam is due to scattering. This had been proved by Paschen⁹ for the infrared radiation of excited helium, and made probable by him also for mercury.

I express my sincere thanks to Professor R. W. Wood for suggesting this problem and for his continuous encouragement and advice, and also to Professors Pfund and Herzfeld for their help.

PHYSICS DEPARTMENT,
THE JOHNS HOPKINS UNIVERSITY,
December 18, 1927.

⁹ F. Paschen, *Ann. d. Physik* **45**, 625 (1914).

BIOGRAPHY

Julius Zbyszko Zielinski, son of Dr. Boleslaw Zielinski and Zofja (Dalmayer) Zielinski, was born October 10th, 1902 in Brzezany, Galizia. He received his early education in the public school in Lemberg, attended the gymnasium in Lemberg, Vienna and Jaslo graduating there in 1920. He served as volunteer in the Polish army during the war against Soviet Russia and was discharged from the army in 1921. Afterwards he studied Physics and Chemistry at the Jeanno Casimiro University of Lemberg from 1921-1925, and obtained a degree corresponding to M.A. (qualification as college teacher). From 1925 until 1927 he took graduate work at The Johns Hopkins University as fellow of the Kosciusko Foundation. He attended lectures under Professors Ames, Wood, Herzfeld, Pfund and Mur-naghan.

